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Analysis of Temperature Elevation in Older Individuals for Far-Field Microwave Exposures

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***Abstract*— In our previous study, with numeric Japanese male model, we clarified the difference of thermoregulatory response between the younger and older adults. In this study, we investigate core temperature elevation and perspiration in younger and older adults for plane-wave exposure at 0.4 W/kg by taking into account the thermoregulatory response of younger and older adults. The frequencies considered were at 65 MHz and 2 GHz. From our computational results, the core temperature elevation in the older adult model was larger than that in the younger adult at both frequencies. The reason for this difference is attributable to the difference of sweating, which is originated from the difference in the threshold activating the sweating.**

I. INTRODUCTION

There has been increasing concern about adverse health effect due to electromagnetic waves. Recently, dosimetry for children has been listed as high priority study. On the contrary, little attention was paid to the adverse health effects due to electromagnetic waves. Several studies reported that the difference in heat tolerance between younger and older adults is caused by a decreased thermal sensitivity [1, 2]. However, it was unclear whether this decreased sweating was caused by a signal from the hypothalamus or the skin (periphery).

The computational approach has become common for estimating temperature and thermophysiological response to heat stress, including microwave-induced temperature elevation. In particular, we developed a computational code that simulates the time evolution of the temperature variation and sweating rate in the numeric human models of adults and children, incorporating a comparison of the computational results with measured data [3]. In our previous study [4], we further developed a thermoregulatory model for the elderly by comparing the FDTD results and measurement [5].

In the present study, based on that computational code and a high-resolution realistic human model, the temperature variation and sweating rate in younger adults (20–30 years old) and older adults (>60 years old) were computed for plane wave exposure at 65 MHz and 2 GHz.

II. COMPUTATIONAL PHANTOM AND METHODS

A. Numeric human phantom

Figure 1 illustrates the numeric Japanese male phantoms. The human phantom of adult male TARO [6] is segmented into 51 anatomic regions like skin, muscle, bone, brain, heart and so forth. The original resolution of the human model was 2 mm. The height, weight, and surface area of the models are

Fig.1. Anatomically based human body phantom

Table.1. Height, weight and surface area-to-mass ratio of Japanese phantom

	H [m]	W [kg]	S [m^2]	S/W [m^2kg^{-1}]
male	1.73	65	1.84	0.028

1.73 m, 65 kg and 1.78 m^2, respectively, corresponding to surface-area-to-mass ratio of 0.0274 m^2 kg^{-1}. This human body model is used both for younger adults (20–30 years old) and older adults since no anatomically based numeric model for the elderly has been developed.

B. SAR Computation

The finite-difference time-domain (FDTD) method was used to calculate the electromagnetic power absorbed in the human models. The FDTD method is most commonly used in the RF dosimetry for its capability to handle lossy dielectric medium like human body. The FDTD grid is discretized at 2 mm so as to coincide with the resolution of the human models. For geometries in which the wave-object interaction has to be considered in open regions, the computational space has to be truncated by absorbing boundaries. We use perfectly matched layers consisting of 12-layer as the absorbing boundaries. The dielectric properties of tissues have been determined from the four Cole–Cole model by [7]. The dielectric properties of tissue types that were not described in [7] have been substituted for those of similar tissues. The dielectric properties of the elderly were assumed to be identical those of the younger adults.

C. Temperature calculation

The temperature elevation in the numeric human models was calculated by solving the bioheat equation [8], which is an equation modelling the thermodynamics of the human body. A generalized bioheat equation is given as:

$$C(\vec{r})\cdot\rho(\vec{r})\frac{\partial T(\vec{r},t)}{\partial t}=\nabla\left(K(\vec{r})\cdot\nabla T\right)+A(\vec{r},t) - B(\vec{r},t)\cdot\left(T(\vec{r},t)-T_b(t)\right) \quad (1)$$

where $T(\vec{r},t)$ and $T_B(\vec{r},t)$ denote the temperatures of tissue and blood, respectively, C is the specific heat of tissue, ρ is the mass density of tissue, K is the thermal conductivity of tissue, M is the basal metabolism per unit volume and B is a term associated with blood perfusion. The values used for thermal parameters are described in [9].The boundary condition between air and tissue for Eq. (1) is expressed as:

$$-K(\vec{r})\frac{\partial T(\vec{r},t)}{\partial t}=H(\vec{r})\cdot\left(T_s(\vec{r},t)-T_e(t)\right) + 40.6\cdot\left(SW\left(\vec{r},T_s(\vec{r},t)\right)+PI\right)/S \quad (2)$$

where H, T_s and T_e denote, respectively, the heat transfer coefficient, the body surface temperature and the air temperature. The heat transfer coefficient includes the convective and radiative heat losses. S is the total surface area of the human body, SW [g min^{-1}] is the sweating rate, and PI, the insensible water loss, is 0.63 g min^{-1} for adults. The value of 40.6 is a conversion coefficient [J min g^{-1} s^{-1}]. The key feature of our computational modelling is that the body core temperature variation can be tracked in addition to the shallow regions of the body, unlike in conventional computational schemes. The blood temperature varies according to the following equation, in order to satisfy the first law of thermodynamics [10, 11]:

$$T_B(t)=T_{B0}+\int_t\frac{Q_{BTN}(t)}{C_B\rho_B V_B}\mathrm{d}t \quad (3)$$

where Q_{BTN} is the net rate of heat acquisition of blood from the body tissues, C_B (= 4,000 J/kg·°C) is the specific heat of blood, ρ_B (= 1,050 kg/m^3) is the mass density and V_B is the total volume of blood. V_B is chosen to be 5,000 ml (ICRP 1975). The thermal constants of the human tissues and the heat transfer coefficients used in the present study are identical to those used in our previous study [3].

D. Thermoregulatory Response

The thermoregulatory response given here has been developed in our previous study [4]. Let us summarize that thermoregulatory model. The sweating for the adult is modelled based on the formulas in [12]. The sweating rate SW [g min^{-1}] is assumed to depend on the temperature elevation in the skin and hypothalamus according to the equation:

$$SW(\vec{r},t)=\chi(\boldsymbol{r})[\{\alpha_{11}\tanh(\beta_{11}\Delta T_S-\beta_{10})+\alpha_{10}\}\Delta T_S +\{\alpha_{21}\tanh(\beta_{21}\Delta T_H-\beta_{20})+\alpha_{20}\}\Delta T_H] \quad (4)$$

where T_s and T_H are the temperatures of the skin averaged over the body and hypothalamus, respectively. $T_{s,0}$ and $T_{H,0}$ represent set temperatures or upper critical temperature of thermoneutral condition [13]. The dependency of the sweating rate on the body part was considered by introducing the multiplier $\chi(\boldsymbol{r})$ based on Table 2 in [12]. The coefficients of α and β are determined for the average sweating rate based on measurements [12]. In Eq. (4), these coefficients are α_{10}=1.20, α_{11}=0.80, α_{10}=0.19, α_{11}=0.59, β_{20}=6.30, β_{21}=5.70, β_{20}=1.03 and β_{21}=1.98.The maximum sweating rate in most body parts except for the legs was confirmed to be almost identical between younger and older adults [5, 14, 15, 16]. Thus, we changed the original equation (4) as follows: *i*) the decline in the sweating in the leg is considered by adding a multiplier $\gamma(\boldsymbol{r})$, and *ii*) the threshold for inducing the sweating response in the older adults is increased by introducing $\Delta T_{S,dec}$ and $\Delta T_{H,dec}$ which represent the decline in thermal sensitivity due to aging. The resulting equation for sweating in older adults is thus

$$SW(\vec{r},t)=\gamma(\boldsymbol{r})\chi(\boldsymbol{r})[\{\alpha_{11}\tanh(\beta_{11}\Delta T_S-\beta_{10})+\alpha_{10}\}\Delta T_S +\{\alpha_{21}\tanh(\beta_{21}\Delta T_H-\beta_{20})+\alpha_{20}\}\Delta T_H] \quad (5)$$

Where

$$\Delta T_S=\begin{cases}0 & T_s<T_{s,0}+\Delta T_{s,dec}\\ T_S-(T_{s,0}+\Delta T_{s,dec}), & T_s>T_{s,0}+\Delta T_{s,dec}\end{cases} \quad (6)$$

$$\Delta T_H=\begin{cases}0 & T_H<T_{H,0}+\Delta T_{H,dec}\\ T_H-(T_{H,0}+\Delta T_{H,dec}), & T_H>T_{H,0}+\Delta T_{H,dec}\end{cases} \quad (7)$$

For a temperature elevation above a certain level, the blood perfusion rate is increased in order to carry away the excess heat produced [17]. The variation of blood perfusion rate in the skin through vasodilatation is expressed in terms of ΔT_H and ΔT_S:

$$B(\boldsymbol{r},t)=(B_0(\boldsymbol{r})+F_{HB}\Delta T_H(t)+F_{SB}\Delta T_S(t))\cdot 2^{(T(\boldsymbol{r},t)-T_0(\boldsymbol{r}))/6} \quad (8)$$

where F_{HB}, and F_{SB} are the weighting coefficients of signal from the hypothalamus and skin, respectively. The coefficients of F_{HB} and F_{SB} in Eq. (8) were 17,500 W/m^3/°C^2 and 110 W/m^3/°C^2 [10]. Blood perfusion in all tissues except the skin was assumed as constant, as is similar to [17].

E. Exposure scenario

The anatomically based human model named TARO is located in free space. A front incident plane wave with vertical polarization was considered as a wave source. The whole body average SAR has two peaks for plane wave exposure at the ICNIRP reference level: namely, it becomes maxima at 65 MHz and 2 GHz. The whole body average SAR scaled to 0.4 W/kg at 65 MHz and 2 GHz.

The duration of exposure was chosen as 1 hour. This duration was chosen so as to be longer than the averaging time of 30 min considered in the ICNIPR guidelines [18] and the thermal time constant for the male with a smaller perspiration rate (52 min.) in our previous study [9].

III. COMPUTATIONAL RESULTS

Figure 2 shows the time course of body-core temperature elevation in the younger and older adults at the whole-body-averaged SAR of 0.4 W/kg. As seen from Fig. 2, the temperature elevation in the older adult is found to be 10% larger than that in the younger adult. In addition, as shown in

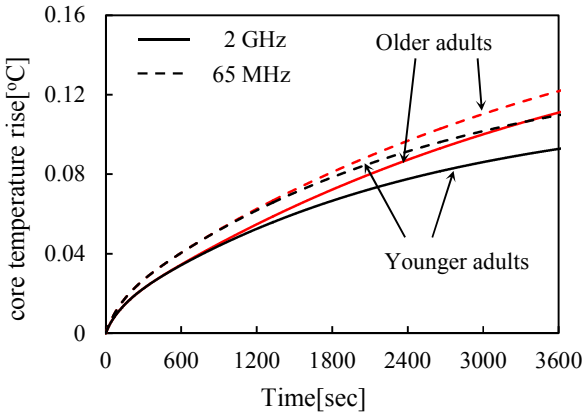
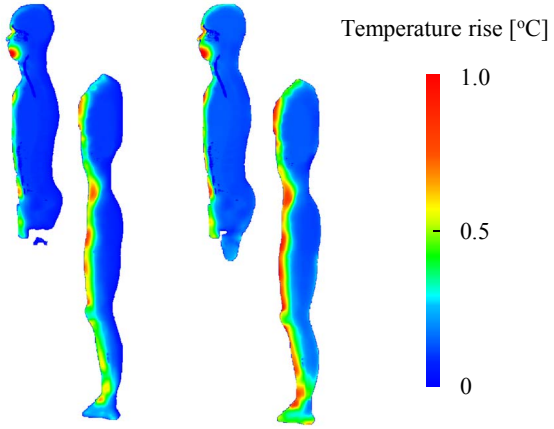


Fig.2. Temperature elevation in the Younger and Older Men at the whole-body-averaged SAR of 0.4 W/kg



(a) Younger adults (b) Older adults

Fig.3. Temperature elevation distributions in (a) the Younger and (b) Older Men at the whole-body-averaged SAR of 0.4 W/kg, The frequency of the incident wave is 2 GHz, respectively.

Fig. 3, the temperature elevation in the older adult was higher than that in the younger adult. Specifically, the mean skin temperature elevations in the younger and older adults were 0.17 °C and 0.33 °C, respectively; the latter temperature elevation is almost twice of the former one. The reason for this difference is attributable to the decline of the sweating rate in the elderly [4]. Amount of sweating reached 30g in the younger adult at 1 hour while it was 10g in the older adult.

IV. Summary

We investigated core temperature elevation and perspiration in younger and older adults for plane-wave exposure at 0.4 W/kg. The model of thermophysiological response developed in our previous study was applied here. From our computational results, core temperature elevation in the older adult model was 10% larger than that in the younger adults at the both frequencies. Similarly, the skin temperature in the elderly was found to be larger than that in the younger adults. The reason for this difference was attributable to the threshold for activating the sweating in the older individuals.

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